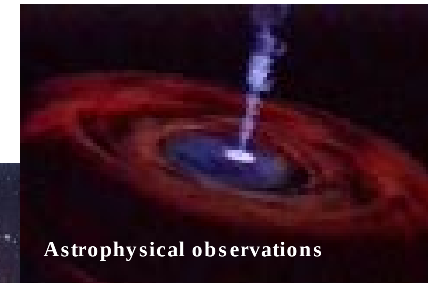
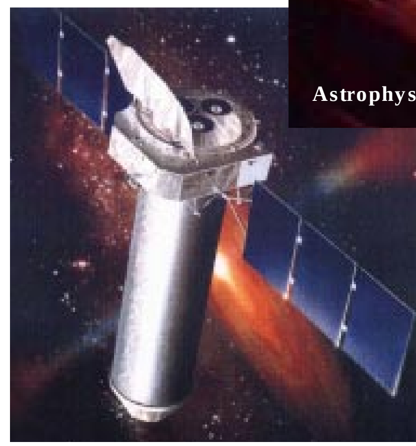
Marrying Astrophysics with the Earth



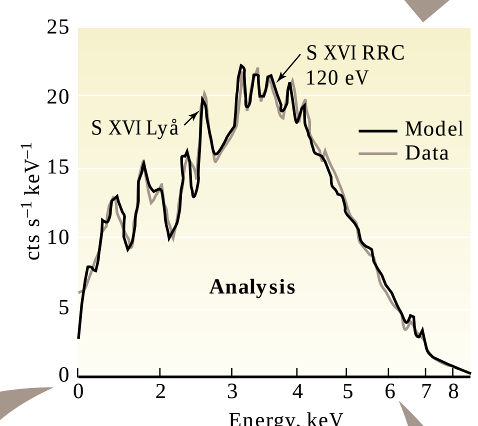


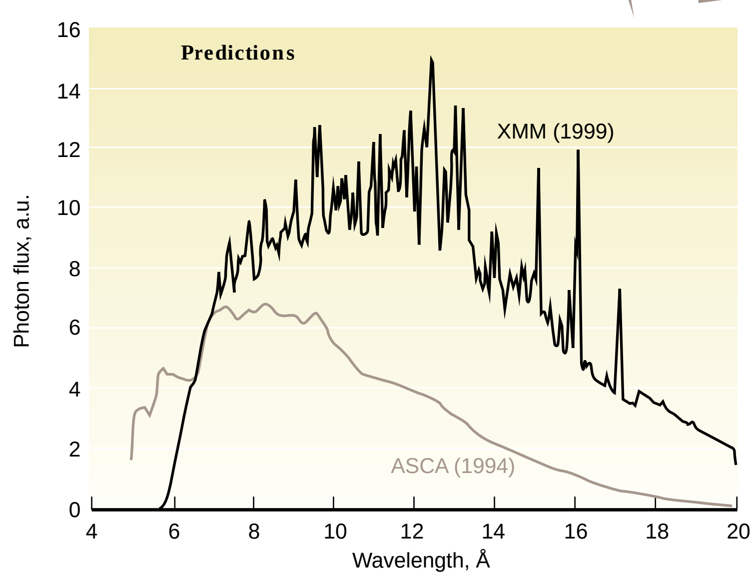
ASTROPHYSICISTS, it could be said, have the universe for a laboratory. And what a laboratory it is, with conditions that cannot be duplicated in an earthly setting—nearly perfect vacuum, extraordinary temperatures and pressures, and enormous distances. But the very vastness that provides these conditions makes study of astrophysical phenomena difficult.

The observable phenomena in the universe often are the result of complex interplay between several physical processes, each of which operates over a scale that cannot be controlled or modified by the experimenter. Obviously, a researcher cannot perform any type of controlled experiment on objects outside the solar system. Theory and computer simulations must be called upon to fill the void left by the absence of controlled experiments.

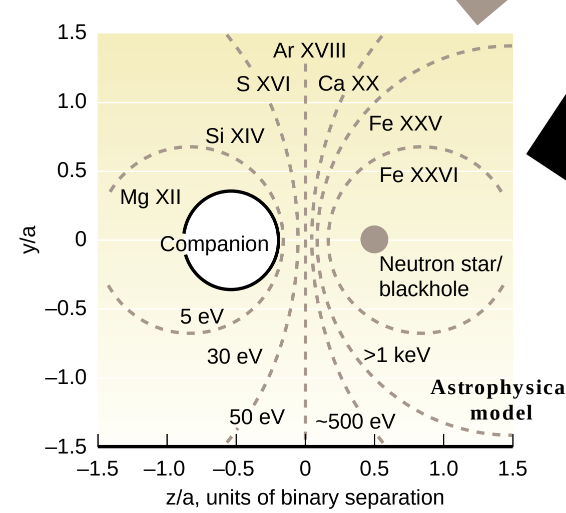
To complement their observations, astrophysicists must leave their laboratory of the universe and return to the more modest facilities on Earth. Lawrence Livermore, with its advanced computational resources and laser plasma research capabilities, is a natural place to conduct this research.

Occupying that particular spot on Earth is astrophysicist Duane Liedahl. Along with astrophysicist Christopher Mauche, Liedahl is working to shed some light on the properties of cosmic x-ray sources while also using the data from space-borne experiments to refine and improve the accuracy of computer simulations of these phenomena.





The interplay of astrophysical research at Lawrence Livermore benefits from unique facilities and capabilities.



Works in Both Directions

The goal of Liedahl's project is to improve and experimentally benchmark a sophisticated suite of computational tools for modeling the radiative properties of astrophysical plasmas. Liedahl and his colleagues are approaching solutions to problems in astrophysics along four avenues: astronomical observations, laboratory experiments, computer simulations, and theory (see figures for the interplay of these approaches). Historically, laboratory experiments have been performed to identify elements by measuring wavelengths that can be matched to stellar spectra. But the interaction of computer simulations and laboratory experiments works in both directions. Data from experiments are used to refine the computer models, and the computer models help scientists understand the problem and develop theories.

Especially now, in the Department of Energy's nuclear-test-free Stockpile Stewardship and Management Program (SSMP), x-ray astrophysical observations and related modeling will play an essential role in benchmarking our ability to understand the physics of thermonuclear weapons because much of the physics is common to both fields. For example, high-quality x-ray observations from satellites may well be the source of future data supporting the SSMP.

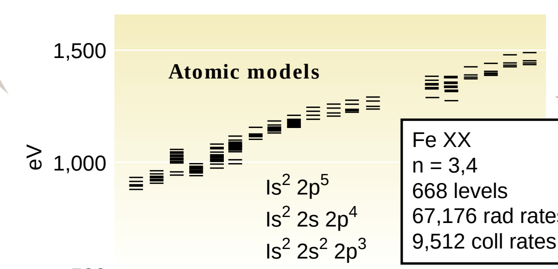
Lawrence Livermore's current leadership position in modeling x-ray sources is a result of its work to understand high-energy-density physics, which is required to predict the behavior of weapons.

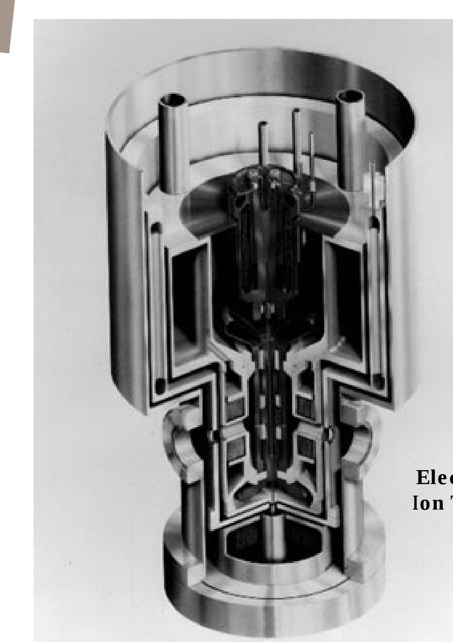
"In short, theory draws from computer simulation, and computer simulation draws from experiment," Liedahl says. "Livermore's computational modeling for the SSMP will benefit from the improved atomic models that allow us to verify the accuracy of our computational models."

Liedahl also works closely with Peter Beiersdorfer of Lawrence Livermore's Electron-Beam Ion Trap (EBIT) facility. At EBIT, measurements of electron-impact ionization, excitation, and recombination can be made that are crucial to understanding high-temperature plasmas. These experiments yield data that can be used to verify the completeness and accuracy of atomic models of the emission properties of various elements involved in astrophysical processes. Liedahl and his colleagues use these improved atomic models, along with data from space-borne experiments, to calibrate astrophysical models. In turn, these improved models allow scientists to refine theories about the behavior of plasmas and highly charged ions—essentially, our basic understanding of matter in extreme environments.

Science Born by Chance

"The science of x-ray astronomy was born in 1962 during a rocket-based experiment to detect x-ray-induced fluorescence on the lunar surface," Liedahl says. "By chance, the Moon's





Electron-Beam Ion Trap facility

orbit passed close to the position of the star Scorpius X-1, and a dramatic increase in flux—changes in the radiation emitted—was detected. This discovery indicated that x-ray observations could reveal new and exotic cosmic phenomena that are largely invisible to conventional optical and radiotelescope techniques."

Our solar system is inside a million-degree ball of gas—purportedly carved out by an ancient supernova—that is radiating x rays. The Sun, because of its proximity to Earth, is our brightest source of x rays. However, most objects in the universe—stars, supernova remnants, galaxies, and black holes—also produce x rays. Scorpius X-1 is a much brighter source of cosmic x rays, 100 billion times stronger than our Sun. But it is also 100 million times more distant than our Sun, and the apparent brightness decreases with the distance squared.

"We've found that x-ray spectroscopy is a very useful measuring tool for cosmic plasmas," Liedahl continues. "However, its real usefulness in astrophysics depends on significant improvements in its sensitivity and capabilities. This usefulness will be realized only after we can make significant improvements in our spectroscopic modeling tools. Some of the unique characteristics of cosmic plasmas include ultralow density (down to 10^{-3} atoms per cubic centimeter, roughly a million times better than the best vacuum achievable on Earth), high radiation-energy density, ultrahigh magnetic fields, relativistic gas flows, and very-high-temperature shock waves."

Traditionally, spectroscopy has been used to identify elements. As data quality improves, the demands placed on spectroscopic models will become much more stringent because astrophysicists will want to know the physical conditions of the plasmas in which the elements exist. Liedahl's approach seeks to identify the detailed behavior of atoms in a wide range of physical environments. His team uses these data to build atomic models to hypothesize about the composition and physical conditions of cosmic plasmas. Then the team uses these atomic models to refine the astrophysical models and improve accuracy.

"Atomic physics operates the same way on Earth as it does in space," Liedahl says. "By improving our atomic models under conditions we can control, we develop the confidence to apply them to more complex astrophysical environments, which we can't control."

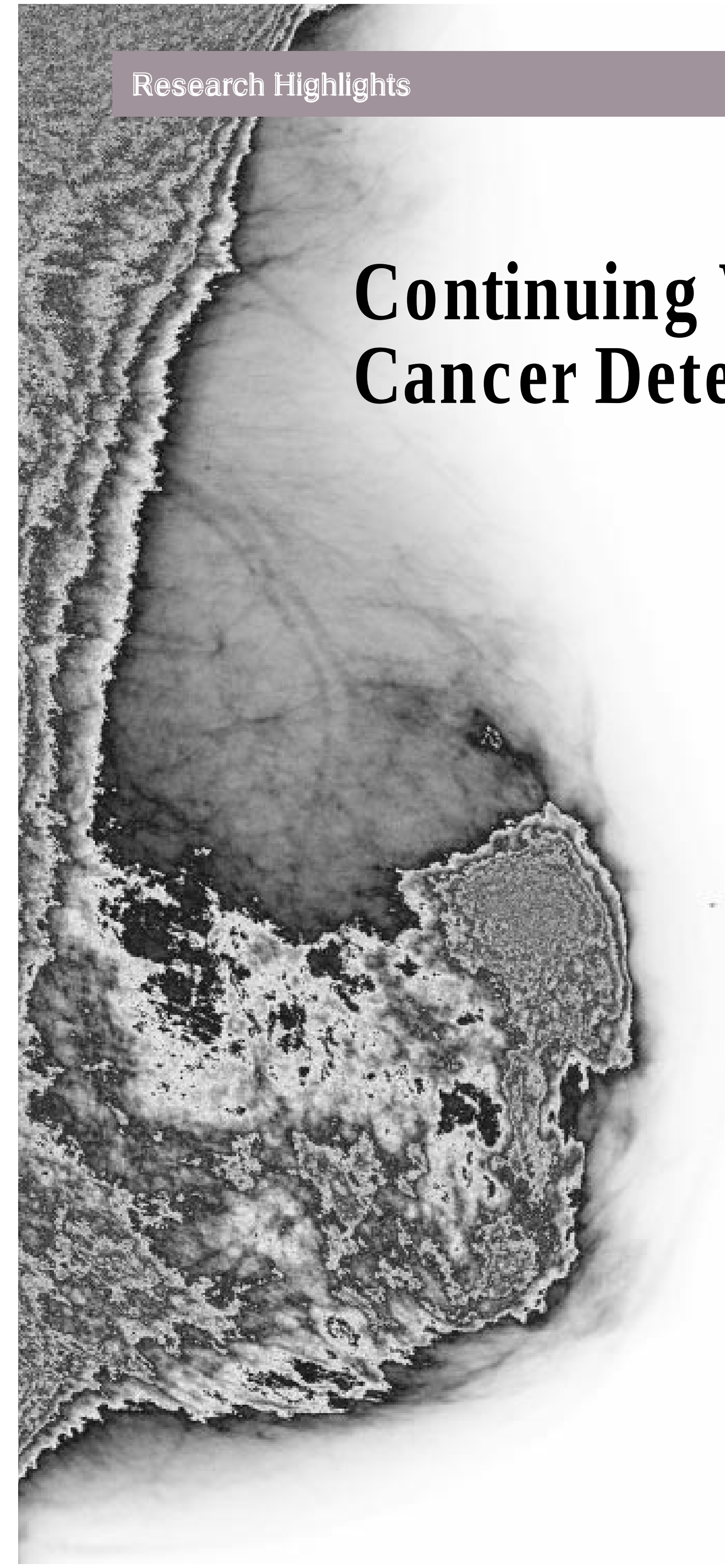
Liedahl's work helps further our understanding of both the relevant atomic physics and the astrophysics of the sources themselves. Unfortunately, acquiring high-quality x-ray spectra of cosmic sources poses experimental challenges because the sources are extremely faint, and observations must be conducted from space. Although the interstellar medium is an extremely good vacuum, it is not perfect and thus is not entirely transparent to x rays. However, our ability to collect high-quality data will be dramatically improved in the near future when new satellites are launched. The U.S. project AXAF; the European XMM, for which Lawrence Livermore collaborated with the University of California at Berkeley to construct the grating arrays in the spectrometers; and Japan's Astro-E will provide more than order-of-magnitude improvements in sensitivity and resolution. "We also are expecting to achieve great improvements in the versatility of x-ray spectroscopy analysis tools," Liedahl adds.

The tremendous quantity of data expected from the new satellites launched by the U.S., Europe, and Japan will provide a basis for significant advances in our understanding of a wide range of phenomena. Lawrence Livermore's ability to coordinate large-scale technology, formidable computational power, and an experienced team of researchers can have a major impact on the astrophysics community by helping to maximize the scientific yield from major space missions.

—Sam Hunter

Key Words: astrophysics, astrophysical plasmas, atomic physics.

For further information contact Duane Liedahl (510) 423-9647 (duane@serpens.llnl.gov).



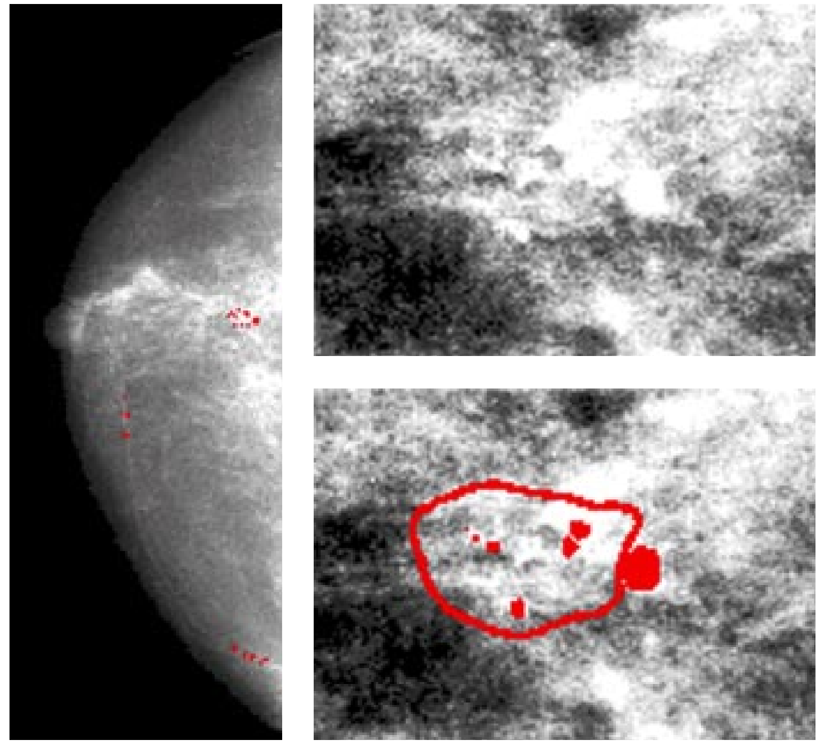
Continuing Work in Breast Cancer Detection Technologies

NEITHER cause nor cure is known for breast cancer, a serious disease that may affect one out of every nine women in the United States. Early detection is the only known means for increasing a victim's chances for survival; mammography is currently the best means of cancer detection in women showing no symptoms.

The power of mammography is proven. Yet, some breast cancers are missed, usually because the cancer is not imaged or because its indications in the image are too subtle to be recognized. The difficulty of visually detecting the cancer's subtle warning signs (in particular, sorting out significant microcalcifications—the calcium-rich deposits that are clues to malignant breast cancers) point to the need to improve image quality and the means of interpreting mammograms.

In 1991, help for improved breast cancer detection came from an unexpected source—Lawrence Livermore scientists and engineers working on national defense projects. They began to recognize that their technologies had important medical applications. Clint Logan, an engineer with expertise in materials imaging, an important aspect of nondestructive evaluations (see article on p. 4 of this issue), proposed using digital computer analysis on film mammograms. His proposal was carried out in a three-part project, first described in *Energy and Technology Review*, Nov.–Dec. 1992, pp. 27–36. The first part was to digitize mammograms, that is, to convert the data on the film record into numbers, applying a high spatial and contrast resolution to the entire mammogram. When digitized, data could be displayed with a variety of contrast settings, which allow clearer viewing than film studied over a light box.

The second part of this work was to develop computer algorithms to automatically detect microcalcifications in the digitized mammograms. The objective was to provide a "mammographer's assistant" that would quickly and objectively detect and flag microcalcifications for radiologists and doctors. The algorithm, developed by biomedical image processing specialist Laura Mascio, first performs two types



The panel on the left is a mammogram with calcifications. The area containing calcifications is magnified in the two panels on the right, (top) without annotation marks and (bottom) with the overlying annotation marks.

of high-frequency analysis on a digitized image. One procedure extracts contrast (intensity difference) information, saving structures that have abrupt changes in brightness (from edges, for example) and are larger than several pixels in size. The other procedure extracts spatial, or size, information and thus saves small, textured structures.

Adding together what has been preserved by the two high-frequency analyses produces an image that is brightest where it contains detail common to both. When a selective erosion or enhancement (SEE) filter is applied over this image, it further reinforces image pixels that show strong evidence of belonging to a microcalcification and erodes pixels that show otherwise. The method developed by Mascio forms the basis of a computer algorithm that distinguishes between microcalcifications and mimicking spots, such as specks and flecks on the film. It was the first microcalcification-detection algorithm to use a gray-scale morphology for extracting frequency and texture information. It served as a model for further development of mammography screening algorithms.

The third part of the project was the design of a filmless, directly digital mammography system. Such a system would provide information and detection superior to the conventional film-based system, yet it would require a lesser x-ray dose to the patient. In collaboration with Fischer Imaging Corp., Logan and Jose M. Hernandez, another Livermore engineer, developed a digital screening unit with a novel x-ray source that can be adjusted for each patient's body size and an image detector that uses a charge-coupled device camera. Early trials indicate that this system yields images with better signal-to-noise ratios than conventional x rays. And because the images are digital, they can be manipulated in terms of contrast, magnification, and area of interest for the best view.

Improving Detection Algorithms

Algorithms having better sensitivity lead to earlier diagnosis of breast cancer and improved long-term survival. Algorithms having improved specificity (that is, they can separate suspicious spots that turn out to be benign from those that are malignant) mean fewer unnecessary biopsies and thereby less cost and less patient anxiety. However, sensitivity must be retained when improving specificity; otherwise, early, curable cancers could be missed.

In recent years, several other institutions have developed algorithms for computer detection of breast cancer. Until

recently, however, there has been no way to compare the different algorithms because each research group has tested its own algorithms on different sets of film images that have varying degrees of diagnostic difficulty. Comparison of their relative performance is important because, in many cases, only partial records have been digitized.

To provide a standardized algorithm evaluation tool, Mascio and other Lawrence Livermore scientists began collaborating in 1995 with researchers from the University of California at San Francisco (UCSF) to compile a library of mammograms that could be used to test detection sensitivities and specificities. They used UCSF screening data of patients whose identities had been obscured. A total of 50 patient cases were selected to represent different categories: 5 normal, average, healthy cases; 5 normal but difficult cases (e.g., with implants, asymmetric tissue); 20 cases with obviously benign microcalcifications; 12 cases of suspicious but benign microcalcifications; and 8 cases of a biopsy-proven, malignant cluster of microcalcification. A radiologist then worked with the Livermore team, using all available clinical information, to annotate the mammograms.

The library is a first step toward a meaningful comparison of microcalcification-detection algorithms. The completely digitized mammograms have been put onto a CD/ROM in binary data format (see photos, p. 24) to make them available for other researchers. Images will be available soon on Lawrence Livermore's Web site (http://www.llnl.gov/).

Another problem with digital mammography is that its very large data files can present storage and processing problems, especially for small clinics with limited computer resources. Digital mammography usually records four views per patient, each taking up 200 megabytes of computer memory. To make this technology more efficient and practical, Mascio has proposed a way to compress mammogram files by factors of 10 to 30 without sacrificing image detail or diagnostic accuracy. Furthermore, it requires no decompression time when data are retrieved for viewing or analysis.

Generally, the more data are compressed, the more the data values differ from their original form once they are decompressed. Mascio's approach, called dynamically lossless compression, avoids wholesale data compression and instead selectively assigns the most data space (i.e., provides the highest spatial resolution) to the features that must be depicted in the most detail, such as detected microcalcifications. Less important features—such as background, healthy, nonglandular tissue—are given coarser resolutions. Thus, an image may contain many different spatial resolutions, each appropriate to the significance of the particular feature, and all based on mammogram-specific knowledge. This compression approach parallels human visual inspections of mammogram film—radiologists use a magnifying glass to get a higher-resolution view for studying microcalcifications, but they inspect larger abnormalities without the magnifier and by standing at a distance from the mammogram.

For the Next-Generation System

As a result of this collaboration, four direct-digital screening systems produced by Fischer Imaging Corp. have been installed at sites around the U.S. Even as they are being introduced to the general population, Jeff Kallman, a Lawrence Livermore engineer, is starting research on the sensors for a new generation of mammography screening. He proposes to generate three-dimensional images of soft breast tissue speedily and painlessly with linear ultrasonic diffraction tomography. Because breast tissue has neither large sonic variations nor appreciable multiple scattering, linear imaging techniques can be used. There is some evidence that cancerous tissue has sound speed and attenuation properties different from normal tissue; the hope is that such an imaging system will be able to distinguish between them.

Data collection would be done while the breast is immersed in water or gel, bypassing the breast compression that makes conventional mammography uncomfortable and even painful for some women. Furthermore, it would involve no ionizing radiation, thus eliminating concerns about x-ray exposure. With appropriate data-acquisition technology, which Kallman is investigating, breast cancer screening in the future would be done quickly as well as safely.

— Gloria Wilt

Key Words: breast cancer, data compression, detection algorithms, digital mammography, linear ultrasonic diffraction tomography, mammogram library, microcalcifications.

For further information contact J. Patrick Fitch (510) 422-3276 (jpfitch@llnl.gov).